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Procedia Manufacturing 3 (2015) 1273 – 1280

Procedia MANUFACTURING

6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, AHFE 2015

Using system architecture considerations to analyze allocation of functions

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Abstract

A number of methods exist for analysing 'Allocation of Functions' (AoF) from a Human Factors Engineering (HFE) perspective (e.g., Fitts List [1]). These methods have been criticised as being of limited practical value in a design and engineering sense. In particular, the fundamental assumption that AoF is a discrete and orderly part of system design, or can be separated from lower-level considerations of how a system function is executed in practice, has been challenged [2]. In response to the priority placed on AoF by nuclear industry regulators and the apparent shortfalls in existing approaches, this paper presents how approaches from Systems Engineering Architecture Description (AD) can be used to address AoF difficulties. AD is defined as the "fundamental organisation of a system, embodied in its components, [and] their relationships to each other and the environment" [3]. An AD representation of a system is expressed as a set of interlinked models. The intention being that the goals, functions, and relationships can be captured and used as aids for discussion and change. By considering the elementary properties of each function, and their structure and relationships as shown via AD views, the following questions can be considered:

- Is the allocation of a function to a particular system actor compatible with the strengths of that actor?
- Do transitions between system functions introduce any adverse effects?
- Does the set of functions allocated to a particular system actor form a coherent grouping?

The AD-orientated approach has been encouraging as it is more closely aligned with modern systems engineering practice. Further work to verify the outputs of the method against existing facilities and designs is proposed.

Keywords: Allocation of functions; Architecture description; Systems engineering

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doi:10.1016/j.promfg.2015.07.271

1. Introduction

Achieving a good match between human and technical system component capabilities is central to Human Factors Engineering (HFE). This fundamental principle has led to a sustained level of interest over many years in the concept of 'allocation of functions (AoF, [4]). AoF refers to both processes and outcomes regarding the configuration of human or technological system components to form a goal-orientated system that carries out a collection of functions. A function in this sense is being thought of as an "*action, task, or activity performed to achieve a desired outcome*" [5].

In HFE, AoF is seen as a key issue as this determines many aspects of the overall system design that will influence human performance and system safety. Interest in the AoF concept can be found in a number of safety-related industries and practices, not just purely within the HFE discipline. For example, debate regarding allocation of functions between drivers and automatic 'driverless train' systems is apparent in the announcements regarding the 'New Tube for London' train design [6]. On the one hand, Boris Johnson, the mayor of London, has been keen to stress the potential benefits of automation (punctuality, removal of human error, increased train throughput and therefore increased capacity and less crowded trains and stations). Critics, such as trade (labor) unions, are concerned about entrusting public safety to a driverless system, as well as the corresponding change of role for the existing train drivers and any associated job losses [7].

As this real-world example shows, AoF decisions cut across several different engineering domains (e.g. HFE, safety, process, production cost and through-life cycle cost). The purpose of this paper is to examine an approach to AoF within a broader design and Systems Engineering (SE) context.

1.1. Current status of allocation of functions

The consequences to performance of mismatched AoF are particularly relevant to the nuclear industry. The regulatory bodies within the nuclear industry recognize this. Indeed, both the International Atomic Energy Agency (IAEA) and the UK Office of Nuclear Regulation (ONR) highlight the role of AoF and recommend that the functional decomposition and assignment process should be a systematic procedure that takes account of human capability [8,9,10,11].

For example, IAEA guidance [8] states, "*the assignment of tasks between man and machine may be the most critical activity in the design of new process plant and major retrofits. It warrants a design approach that is commensurate in quality with high levels of plant safety and production performance sought from nuclear plant."*

This in turn has been reflect in the UK Office of Nuclear Regulation (ONR) Safety Assessment Principles [10] and the Guidance on 'Allocation of Functions Between Human and Engineered Systems' [11]. The UK ONR Safety Assessment Principle EHF2 [9] states that: "*When designing systems… the allocation of safety actions between humans and engineered structures, systems or components should be substantiated*."

Therefore, it can be seen that there is keen interest from nuclear regulators, asset owners, and safety organisations that AoF be accounted for in engineering and operation activities.

It has been noted that AoF terminology can be unclear [2]. The phrase "allocation of functions" can be used to refer to a number of different things: a design stage, a type of design review, or a resultant design output. The lack of precision in the associated terminology is reflected in the statements from the IAEA and the ONR: on the one hand the IAEA refer to AoF as a design stage, and the ONR appear to refer to AoF as a resulting system design. In practice the difference may not be so great but it does reflect some ambiguity in the fundamental assumptions.

Within the nuclear industry guidance documents [9] and other associated good practice [12,13,14] a general-purpose allocation of functions methodology can be summarised. A process with five general stages can be compiled from the approach covered by these reference sources:

1. Identify the functions that need to be performed;
2. Develop a requirements specification including HFE requirements and scenarios;
3. Identify allocation of function options;
4. Allocate functions to human and technical system components; and,
5. Assess, verify and validate the resultant allocation of functions.

The details of these steps vary by the particular approach being followed, but for the purpose of this paper these steps will be taken to represent some level of recommended approach to AoF within the nuclear industry.

Different approaches and philosophies have been applied when making functional allocation decisions (step 4 in the process above). Bailey [13] and Nemeth [14] in particular provide an overview of the various approaches. The most established approach is the comparative approach. Under this function allocation approach, functions are assigned primarily according to the intrinsic capabilities of humans and machines. Comparison is at the foundation of Fitts List [1], the original and one of the most established AoF approaches.

1.2. Criticism of present allocation of functions approaches

Over the years a number of criticisms have been made of the concept of AoF [2,15,16]. These criticisms also apply to some extent to the guidance concerning AoF within the nuclear industry, as represented in the generic five-step process illustrated above.

Criticisms of AoF have been wide-ranging, and include commentary on the assumptions regarding human and technological system components within Fitts List approaches [15] and also the basis of human-machine comparison as a decision-making approach [16]. This paper will focus upon one particular strand in the commentary: that of AoF as a rational, top-down functional allocation process that can be addressed separately from lower-level details of how a particular function may be implemented within a system.

In particular, the fundamental assumption that AoF is a discrete and orderly part of system design, or can be separated from lower-level considerations of how a system function is executed in practice, has been challenged [2]. This assertion makes particular sense in relation to the nuclear industry where the design philosophy for most modification and replacements to existing plant is one of minimal change [10]. When changes are made, for example to accommodate decommissioning activities and processes, this may involve introducing or altering the resultant AoF between people and technical system components (due to some level of automatic control or improved data acquisition or processing), or between different staff roles. As part of this engineering change process, some level of safety justification may be required. In turn this may require some level of HFE assessment and endorsement, including that of the resultant AoF. In practice (especially in relation to safety functions) there may be an implied AoF and the question may be more about whether this is acceptable rather than whether it is preferable. The notion that AoF considerations should be undertaken in a top-down, conceptual manner is not a practical approach given the regulatory, technological, and historical constraints inherent in the majority of projects.

However, there may be occasions where a formal assessment of AoF is required in order to substantiate that a human-machine system design is appropriate given the level of risk and the safety-significance inherent in the plant functions. This assessment must be undertaken independently of any implied constraints, and focus only on the suitability of the resultant design. It is often necessary to integrate this HFE AoF assessment into activities conducted within other engineering disciplines (for example, safety engineering or systems engineering). However, common AoF approaches do not place any emphasis on integration of HFE AoF models and findings with broader project engineering concerns.

Task Analysis or Hierarchical Task Analysis (HTA, [17]) is often associated with consideration of AoF factors from the HFE perspective [9]. HTA, while a popular technique, does have some disadvantages as traditionally performed within HFE. In particular, as often practiced, the method has difficulty in representing complex interactions and communications across teams of people [18]. Also, HTA focuses on activities carried out by humans - the behavior of technological system components in response to human actions is difficult to model. Given that AoF should be concerned with the overall system behavior and the assignment of functions across people and technical system components, this is a shortfall in the present HFE approaches to AoF.

In addition, some authors [2,19] suggest that an appropriate AoF in a real system is difficult to assign or judge *a priori*, and therefore functional allocation via comparative methods is a flawed approach [16]. This is because the introduction of automation will change work practices in a number of ways that are not easy to identify during traditional design processes (as illustrated by the concept of the task-artefact cycle [20]). Dealing with the effect of emergent work practices due to technology introduction has been addressed by a number of researchers [18], and continues to be an influential factor in practice. Also *how* functions are implemented (and how they are specified), rather than just *who by*, is important in terms of the overall AoF and system performance [21]. Any assessment of AoF should be capable of dealing with the definition of functions in a systemic, systematic and consistent way, in order to mitigate problems associated with poor specification or under-specification of system functions.

One theme that can be drawn from the stated criticisms is that there is little consensus as to the basis for AoF decision-making [2]. However, it can be concluded that good practice suggests that any decision-making should be multi-disciplinary, because engineering of modern nuclear plants and facilities is evidently multi-disciplinary.

Taking these criticisms together, a number of conclusions and questions can be formed from consideration of the current status of AoF methods in practice:

- The definition of a 'function', and the traceability of this representation to wider business needs or safety engineering / systems engineering analysis is unclear;
- AoF approaches do not stress the need for shared representations of proposed or resultant AoF outcomes across systems engineering disciplines; and,
- Cross-disciplinary consideration of AoF appears to be implicit in the existing assignment methods, rather than explicitly referenced, if at all.

Given that HFE is often considered to operate from a systems perspective [22], and that increasing the extent of cross-discipline communication and collaboration may enhance AoF activities, one potential work-around for these drawbacks may be to draw upon existing Systems Engineering models and methods.

2. Model-based systems engineering and systems architecture description

ISO/IEC/IEEE 42010:2011 [3] is an international standard that defines requirements on methods for describing the fundamental concepts, properties, and relationships within a system (a systems architecture). The expression of a system's architecture is known as an architecture description (AD) within ISO/IEC/IEEE 42010:2011.

Architecture description is a reasonably new aspect of Systems Engineering and as such the uptake of the approach is variable [23]. However the intentions of the system's architecture approach are of particular interest to those seeking to improve the consideration of AoF in systematic ways:

- AD is intended to assist in the understanding of the properties and structure of the system-of-interest;
- AD intends that this understanding should be communicated and shared across the stakeholders that have a particular concern toward the system – ISO/IEC/IEEE 42010:2011 stresses that AD should be a tool for co-operation and improved integrated decision making. Much of this is about communication and providing understandable and practicable ways to highlight and solve problems.
- AD should augment or complement existing methods, tools, and techniques.

There have been a number of attempts to move HFE and ADs closer together [24, 25]. Within the HFE community, there has been renewed interest over the past decade in a systems viewpoint in both research and practice [22]. This trend re-states the 'socio-technical system' as important unit of analysis for HFE.

The potential benefits that ADs give to the Systems Engineering discipline also apply to the HFE technical discipline. ADs should enable HF Specialists to collaborate with colleagues from other engineering disciplines, reduce the duplication of effort that can be involved in constructing system models, and improve efficiencies and effectiveness through the use of common languages and frameworks.

One theme in the attempts to improve integration between HF and ADs is that of the 'Human View'. Within DODAF-derived ADs (e.g., MODAF) there has been effort over recent years to produce 'Human Views' that exist within the AD [25]. These architecture views (with an associated collection of viewpoints) are intended to capture people-related or people-focused concerns for stakeholders associated with the system of interest.

The main benefit of the 'Human View' approach is that it provides specific viewpoints to collect human-related concerns - therefore it provides a method by which these issues can be included in the system architecture modeling undertaken on a particular project. This means that the potential benefits of a common modeling approach can be realized.

With regard to AoF, a systems architecture approach that takes forward some of the 'Human View' concepts would mean that some of the potential current drawbacks of current HFE methods could be addressed. In particular, cross-disciplinary communication and systemic and systematic definition of functions could be addressed.

3. Representing allocation of functions within model-based systems engineering

This section presents an example of how the AD modeling approach has been used to inform HFE analysis of AoF in industry. The details of the study are confidential; therefore the examples have been made generic.

The case study is based on a generic dry waste sorting activity that may be common to many types of decommissioning or waste processing facilities. The functional goal of the overall system is to ensure that only certain types of waste enter a downstream process. This involves examining a batch of dry waste, identifying items within the waste based on various properties such as size and material composition, removing these undesirable items from the waste, and then moving the remaining waste to the downstream functions within the process.

The type of AoF analysis being demonstrated here is a review of a proposed initial system design. Within the model of AoF terminology presented above this is the second definition: AoF as a review process of a proposed allocation of function. When the analyst joined the project certain AoF decisions had already been made: for example, it was already decided that the sorting activity could only be performed remotely and would utilize CCTV images, sensors to scan the composition of the waste, and a manipulator arm to remove items from the waste table.

The example presented here is mainly concerned with the *representation* of AoF system designs and associated concerns, as this was the theme discussed in the criticism of nuclear industry AoF approaches in Section 1.2. The focus of this example is on demonstrating how communication and engineering integration can be improved.

The decision-making aspects and assessment of AoF was based on considering the following questions:

- Is the allocation of a function to a particular system actor compatible with the strengths of that actor?
- Do transitions between system functions introduce any adverse effects?
- Does the set of functions allocated to a particular system actor form a coherent grouping?

The TRAK Architecture Description Framework [26] was used to produce a set of a system models. TRAK is a set of linked AD views that can be used to model different parts of a system and the interactions and dependencies within it. The models are linked because an element on one AD can appear on a different AD. For example, an Operator can be shown at the center of one AD where all of the functions assigned to them are represented. That same Operator representation can also be shown on a different AD that focuses on the sequence of activities. In both cases there is conceptual continuity, but without the need to show all relationships and elements on one model.

Using TRAK as a work domain analysis method allowed the concepts underpinning the joint socio-technical system to be highlighted. A number of different TRAK diagrams were used during this functional analysis phase.

Figure 1 presents an AD diagram that shows the functional hierarchy of the waste sorting activity. In this diagram it can be seen how the AD approach allows the analyst to link the functional model with higher-level business objectives and requirements. For example, the function of 'sort dry waste' is linked to a conceptual (logical, implementation-free) activity, which in turn is linked to an underlying requirement (which was taken directly from the conventional engineering schedule of requirements).

This approach is beneficial as it allows the functional model to be seen in context with requirements, and in particular any safety functional requirements that arise from the safety assessment. Placing the safety requirements in context with the functional hierarchy is beneficial for AoF analysis as there may be a required or implied AoF implicit within the safety requirement, for reliability or substantiation reasons. The safety requirement may mean that a particular functional allocation is required or mandatory [27] – for reasons of human health, for example.

Linked to the functional hierarchy is the solution structure. This AD is intended to describe the structure or relationships within a part of the system under consideration. A solution structure block diagram for part of the waste sorting activity can be seen in Figure 2.

Figure 2 shows a number of aspects of the proposed system design. In particular, the sequence in which functions must occur is shown on this diagram through the 'precedes' relationship. The functions assigned to a

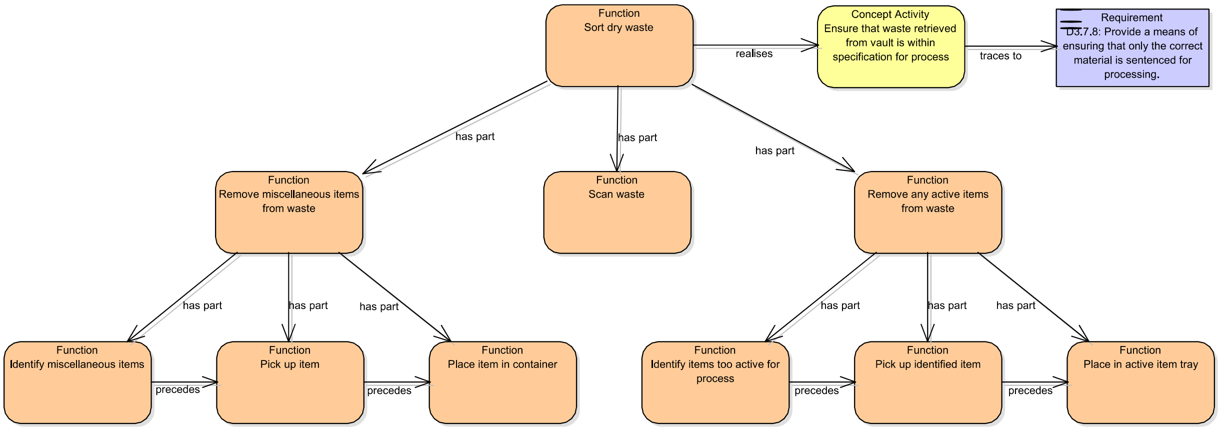

Fig. 1. Functional Hierarchy.

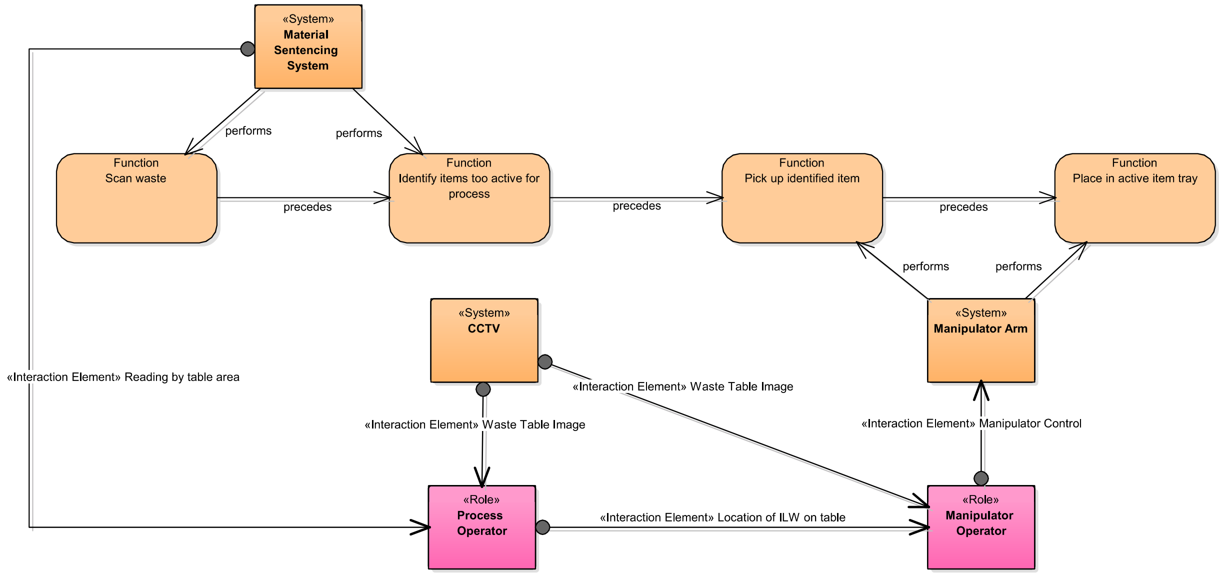

Fig. 2. Structure of the Proposed Functional Solution.

particular system component (human operator or technological system) are shown via the ‘performs’ relationship. Information passing between system components can be seen in the ‘interaction element’ relationships.

It can be seen that, when compared with a more traditional HFE work model representation such as a HTA, the solution structure AD is much richer in information and also able to capture the interactions between system components in relation to the allocated functions.

Figure 2 also demonstrates how the AD approach links diagrams and information representations together. The functions identified in the hierarchy within Figure 1 are carried over to show the sequence on Figure 2. Each AD focuses on a single viewpoint (hierarchy and sequence); this makes the diagrams easier to understand, while still consistent.

It is apparent, even without applying a formal AoF decision-making methodology, that Figure 2 highlights a particular difficulty with the structure of the solution to the waste sorting activity. In this case the Process Operator monitors the output from the instruments that scan and sentence the waste, and then must pass this information on to the Operator of the robotic manipulator. In AoF terms, the Process Operator is not performing a task (repeating of information) that takes advantage of human abilities.

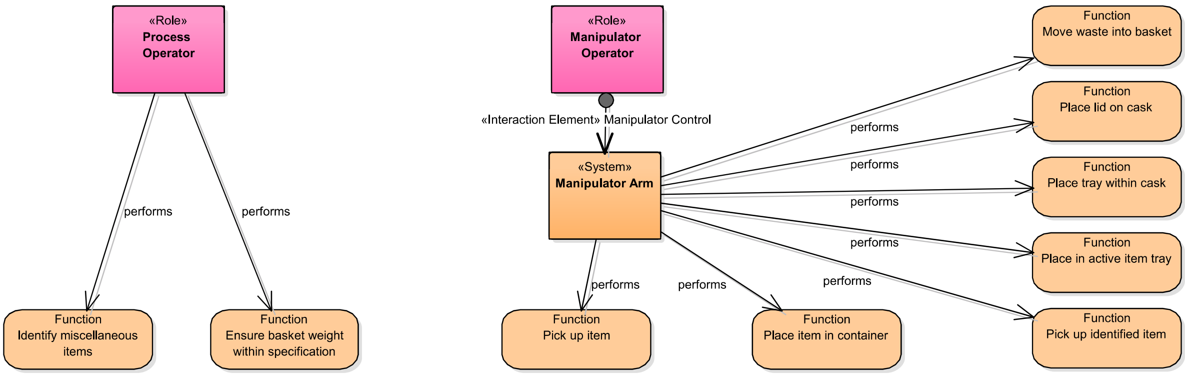

Fig. 3. Assignment of Functions to System Components.

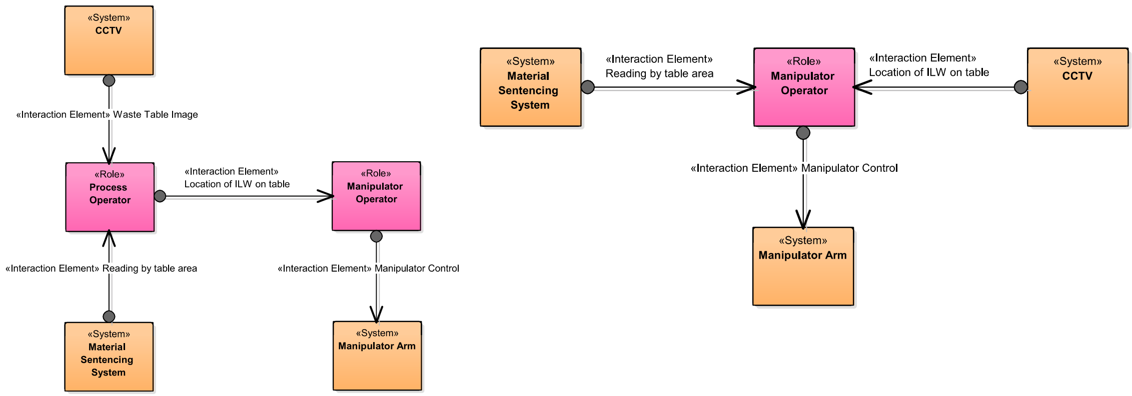

Fig. 4. (a) System Interactions with Process Operator; (b) System Interactions without Process Operator.

This theme is further developed in Figure 3. Figure 3 shows a solution function viewpoint that captures the functions assigned to system components. It does not illustrate the sequence in which functions must occur.

Figure 3 shows the functions that are assigned to two of the operators within the overall waste sorting activity. As can be seen, the majority of the functions are assigned to the Manipulator Operator. The Process Operator is assigned two monitoring tasks. On the basis of a Fitts List type of approach, this would not be viewed as an appropriate allocation of functions.

This can be illustrated in particular in Figure 4. Figure 4 shows the interactions between the system actors (operators and technological system components). Figure 4 clearly shows that the Process Operator, in the system design assessed, is acting more as a conduit, passing information on to the Manipulator Operator.

On this basis the HFE AoF analysis suggests that the role of the Process Operator was poorly defined.

This short example shows how AD system model representations can be used to represent AoF options and solutions in a way that supports multi-disciplinary decision-making. The AD representations can support decision-making around three aspects of appropriate AoF design: the extent to which system functions at the logical level are correctly and adequately defined within HFE in a manner that is at the correct level of detail but still traceable to Systems and Safety Engineering (Figure 1); the expression of functional sequences so that transition between functions and system actors can be understood over time (Figure 2); the extent to which functional allocations form appropriate and meaningful roles for the human actors (Figure 3); and how the interaction of functions may or may not relate to the inherent capabilities of that particular actor type (Figure 4).

4. Conclusions

Allocation of Functions is an on-going concern within the nuclear industry because the overall socio-technical system design, and the role of humans within that system, is of critical importance to safety. However, dissatisfaction exists with present AoF approaches and methods, both in terms of the theoretical underpinnings and the practicalities of conducting these approaches within the context of a multi-disciplinary facility design project.

While some authors have suggested that AoF is flawed in concept, we have focused on improving AoF by bringing the method closer to Systems Engineering, and in particular the emerging field of Architecture Description.

Architecture Description allows AoF concerns to be expressed in terms that can be understood by the wider engineering community (principally systems and safety engineers). This increases the visibility of HF concerns as they can be presented in relation to standard engineering deliverables and practices.

We have found that this allows consideration of AoF along three dimensions: the inherent capability of a particular system actor to carry out a function, functional sequence and transitions, and human role definition.

AD does have some disadvantages. Some Engineers find the models to have insufficient context. However, AD models could use representative illustrations of each element and transaction, or be annotated with more realistic examples and narratives. In the future we hope to include these 'rich picture' considerations within AD modeling.

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